flexibility to implement adaptive management by ensuring that the details of practices implemented for each crop and in each field are documented but kept private, and 3) publicly reporting progress in using indicators or measures of performance reflecting the economic, social and environmental pillars of sustainability. These principles are at the core of a management system consistent with international principles of accountability for sustainability performance.

Example – Managing Phosphorus Fertilizer in the Lake Erie Watershed

Phosphorus (P) is an essential nutrient for growing crops. But in the wrong place – in excess concentration in streams, rivers, and lakes – it can lead to algal blooms. In the Lake Erie watershed region in and around the state of Ohio, USA, levels of dissolved P in rivers and algal blooms in lakes have been trending upward from 1995 to 2011. Fertilizers applied to the predominant corn-soybean cropping system are not the only cause, but are one possible cause among many.

Research data show that when fertilizer P is broadcast and left on the surface, runoff resulting from rainstorms within a few days of application is enriched in dissolved P to levels far above those known to stimulate algal blooms, even though the losses amount to less than 5 to 10 percent of the fertilizer P applied. To mitigate these losses, 4R Nutrient Stewardship implemented in this region focuses on applying fertilizer at the "right time" and in the "right place." Wherever possible, fertilizer P is recommended to be placed below the soil surface, by injecting, banding, or by incorporating after broadcasting. Where incorporation is difficult, for example in no-till systems, producers are advised to pay close attention to the weather forecast, and avoid broadcasting P fertilizer when there is more than 50% chance of intense rain within the next few days.

A group of agri-business partners, government agencies and environmental organizations is working together to provide educational programs and raise awareness of how nutrient stewardship can contribute to reducing losses of dissolved P. This group includes The Nature Conservancy, the Ohio Agri-Business Association, the Ohio government departments of agriculture and natural resources, Ohio State University Extension, and several agri-retailers and crop producers. Further work is ongoing to develop better validated criteria for selecting practices, based on research monitoring actual edge-of-field losses. Further information on the program is available from The Nature Conservancy. By supporting management that is adaptive and addressed at economic and environmental goals at the same time, 4R Nutrient Stewardship assures continued progress in advancing crop yield s in this highly productive watershed.

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Learning from Long-term Experiments – What Do They Teach Us?

By Rob Norton, Roger Perris, and Roger Armstrong

Established in 1916, the Longerenong long-term rotation provides a platform for evaluating long-term trends in farming systems and soil health over a period of many years. Longerenong rotation 1 (LR1) gives us essentially the same message as other long-term agronomic experiments. The message is that rotations can be sustained and productive provided the challenges of diseases, weeds, soil structure, and nutrient replacement are met.

Long-term agronomic experiments (LTAE) reflect new ideas and practices in farming systems. The longest running experiments were established at Rothamsted in the United Kingdom (UK) in 1843, and seven are still running today (Rassmussen et al., 1998). There are only 10 others of these classical (more than 50 years) experiments across the globe, including

LR1 in Australia.LR1 is Australia's longest running annual cropping system experiment, established in 1916 on a self-mulching, alkaline Grey Vertosol near Horsham in southeastern Australia. Average annual rainfall is about 420 mm. LR1 sought to identify what crop sequences would provide improved yields and over time it has became a platform for other research such as on the use of superphosphate. The experiment compares seven cropping rotations and although not spatially replicated, each cropping phase is present every year. The rotations are continuous wheat (WWW), wheat/fallow (WF), wheat/oats grazed/fallow (WOgF), wheat/barley/peas (WBP), wheat/oats/peas (WOP), wheat/oats grazed/fallow (WOgF) and wheat/oats/oats grazed/fallow (WOOgF). The crops receive no fertilizer N, 10 kg P/ha on cereals, and 5 kg P/ha on other harvested crops. Crop establishment, weed control, and crop protection activities follow district practice. In the soil, N and P are present in a range of forms that have different availabilities to plants. Most of the soil N is present in organic forms which are mineralised to nitrate which is the form that plants can take up. Applied P is partitioned into a range of soil pools with different plant availability, due to differences in desorbtion, dissolution, and mineralisation rates that contribute to plant P nutrition.

Soil tests can distinguish the more available P (e.g. resin, bicar-bonate, and sodium hydroxide extractable) forms in the soil (Hedley et al., 1982). Understanding the fate of this applied P helps us predict future P strategies.

The 90+ years of this experiment have given several lessons about grain yields, nutrient removals, and sustainability.

Lesson 1 – Yields can be sustained over long periods

The mean wheat yields over the period of the experiment are shown in **Figure 1**. There are phases in these trends and the most recent recovery, starting in 1975, is co-incident with the use of herbicides on this experiment (Hannah and O'Leary 1995). Over the past 10 years, the rotation experiment has been challenged by the root nematode Pratylenchus and infes-tations of the weed bromegrass, but the downward trend seen in **Figure 1** since about 2000 is a result of low rainfall over that time. The only rotation that did not trend downwards is the WWW, which was already low yielding.

The highest producing rotation (WBP) from LR1 produced two and a half times the energy equivalence of the WWW rotation (2.22 t/ha/y glucose equivalence versus 0.87 t/ha/y glucose equivalence). Glucose equivalence is the energy content of the grain and provides a way to compare yields of different crops with different energy densities. Over the past 90 years, the WBP has produced 1.52 t/ha of wheat, 1.53 t/ha peas, and 1.57 t/ha barley in its 3-year cycle. At current grain prices, this is the most profitable rotation. Although damag-ing to soil structure, the inclusion of a fallow phase into the rotations gave lower yield variability than continually cropped rotations, especially in these years of low rainfall over the past decade (**Table 1**).

Weed and disease control strategies both require biological diversity in the farming system. Crop rotation is fundamental to ensure sustainable production systems with each phase acting as a tool to support and enhance the following crops by providing disease breaks, opportunities for alternative weed control strategies, and/or improving soil conditions.

LR1 has a history of providing lessons to farmers and scientists. This photograph was taken at the annual field day in 1930.

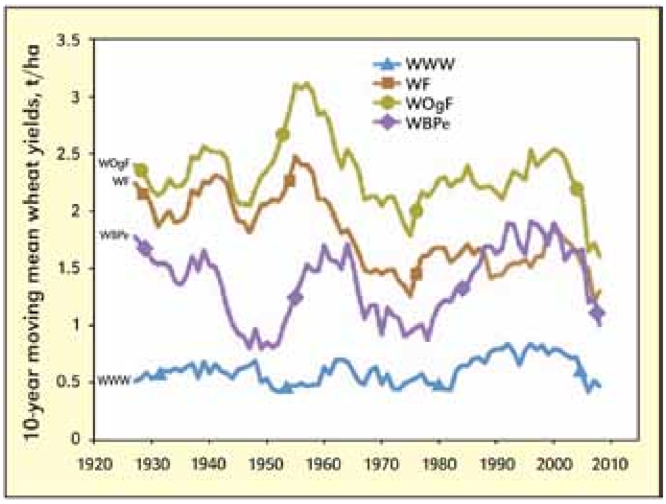


Figure 1. Grain yields of four of the seven rotations from LR1. Data presented are the 10-year moving means for the wheat phases of the rotations for the period 1916 to 2008.

Lesson 2 – Nutrient balances need to be addressed

Long-term production does come at a cost, though. **Table 1** shows the N and P balance for LR1 over the past 25 years. This period was chosen because the experiment was altered a little in 1984 and since then south-eastern Australia has experienced a long period of below average rainfall.

Table 1. Apparent mass balances for N and P for the seven rotations of LR1 (1986-2008).

Rotation treatment 1986-2006	Average wheat yield, t/ha	P balance, Δ kg P/ha/y	N balance, Δ kg N/ha/y
Continuous wheat	0.64±0.52	7.3	-7.3
Wheat:fallow	1.50±0.76	0.9	-11.8
Wheat:grazed oats:fallow	2.05±0.97	-0.3	-10.6
Wheat:barley:peas	1.46±1.31	3.2	2.9
Wheat:oats:peas	1.39±1.24	1.2	1.8
Wheat:oats:fallow	1.86±0.95	3.0	-13.9
Wheat:oats:grazed oats:fallow	2.11±0.96	-0.1	-12.1

Grain yield has been recorded each year and grain protein (N) in recent years. However, seed P content has not been measured, but estimated from other experiments. To develop a nutrient balance for this experiment, the apparent balance of N or P was calculated on an annual basis as:

N balance = N applied as fertilizer + N fixed by legumes – N removed in grain

or **P balance** = P applied as fertilizer - P removed in grain

No estimates were made for free living N fixation, non-biological N inputs, N leaching, N volatilization, or N lost in soil erosion. The N2 fixation for the pea phases were estimated using the peak biomass for peas from the pea grain yield, as suming a harvest index of 0.3, then converting this peak biomass to N fixed by using the conversion of 25 kg N/tonne of biomass (Peoples et al. 2001). Grain N removal was estimated by the grain N content multiplied by the yield of peas, barley, or wheat.

Longerenong College open day in 1930, putting new cultivars in front of farmers.

Longerenong College was one of the first places in southeastern Australia to trial superphosphate for grain production.

Both the grazed oats and the crop stubbles were retained within the plots. Grain P content was estimated from grain P contents taken in 2005, but the actual grain P contents may differ in response to different soil P levels.

Table 1 shows an average N removal of 12 kg N/ha/y from 1984 where no pulse was included and a slightly positive N balance where the rotation included peas.

There was no baseline soil archived when the experiment was established 90 years ago, and so a "fenceline" sample was taken in an uncultivated area adjacent to the site. The soil N and C values (top 10 cm) measured then are in general agreement with the estimated N decline from the mass balances. While it is not possible to fully analyze these data due to the nature of the experimental design, there is an indication that C:N ratios are higher for rotations that have fallows, reflecting the gradual decline in the amount and nature of the organic matter present.

Table 1 also shows the P balance for the various rotations at LR1. Tang et al. (2006) reported P fractionation of the soils from this experiment and a summary of some of these results is given in **Table 2**. All rotations show a positive P balance except for the two grazed oat rotations.

Table 2. Soil N, C, bicarbonate extractable P (Olsen P), total P, and selected P fractions as a percentage of total P for rotations of LR1 and the adjacent uncropped fenceline, when sampled in 2005.

	WWW	**WF**	**WOgF**	**WBP**	**WOP**	**WOF**	**WOOgF**	**Fenceline**
Total soil N %	0.070	0.056	0.063	0.085	0.087	0.061	0.066	0.162
C: N ratio	13.3	16.2	14.9	13.0	12.9	13.9	13.8	13.1
Total P, mg/kg	486	367	307	341	329	330	322	295
Bicarbonate Ext. P, mg/kg	69	52	40	40	47	66	50	18
% HCl P	39	25	18	25	22	23	19	7
% Residual P	35	43	47	49	52	50	61	75

Roger Perris (left) in LR1 plots with second year agronomy students from The University of Melbourne.

The total amount of P and the less available acid-soluble P fraction increased in all rotations, especially in the continuous wheat which also had the highest P balance. The regular P applications used as part of the cropping practices in this experiment increased the total P content of the soil, while the relative proportion of P in the "plant available" pools decreased.

Where is the N coming from? Unfortunately, LR1 had no soil samples archived from the beginning, but we can look at fenceline soils as a measure of "native" soil levels. **Table 2** shows the soil N and C levels. It is possible to estimate the annual decline in soil N from these data, if we assume the starting point was the fenceline soil. These values are largely consistent with the mass balance estimates and indicate that the decline in N is basically derived from the mineralization of organic matter. The conclusion then is that to access N in rotations, soil organic matter needs to be oxidized, and N from the soil comes at a cost to soil C. We need to consider the converse of this statement, which is that if we wish to sequester C in soils, N (and P) will need to be supplied.

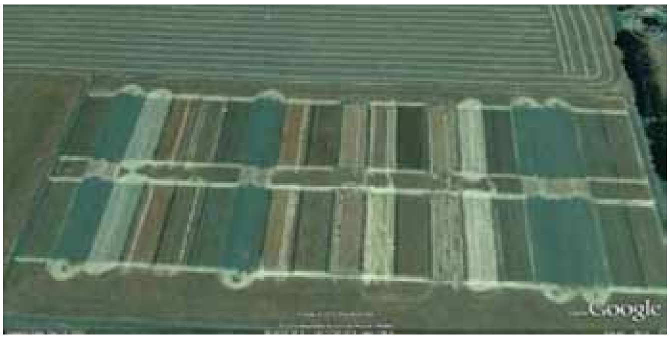
Where is the P going? It is clear that the long-term P applications have raised the total amount of soil P, basically in accord with input and outputs presented in **Table 1**. The soil P fractions differ in their availability to crops and these results show that almost all the applied P is now in the low availability pool (Residual and Acid P). Tang et al. (2006) took soil from these rotations and tested the crop response to P in a glasshouse. This showed a positive response to additional P which is not what would be expected from the Olsen soil P test values. The conclusion is that on these alkaline soils, the fixation processes are rapid and current commercial soil tests are not very reliable indicators of potential P response, and indeed the responses differed among a range of crops used to test response. Those authors also concluded that the key to improving P use efficiency is to match P fertilizer applications to crop P removal on these soils.

Soil C levels The effect of mineralizing N is to reduce C so that soil C levels have declined. With the current interest in C sequestration, LTAEs such as LR1 can provide unique real world data on soil C stocks under different farming systems. In 1916, when the experiment was established, such a question would not have been thought of and now as part of a new research project, this site will be used to measure soil C stocks to depth and accounting for soil bulk density.

Conclusion

At the most fundamental level, LTAEs provide us with reassurance that cropping and pasture systems can operate for many decades and depending on the strategies adopted, continue to produce food and fibre with resource protection. While cropping and pasture systems computer simulation models can help refine information, they do require real world data to calibrate against. Conclusions based on 10 to 20 years of experimental data can be quite different to those based on 50 years of data. Long-term agronomic experiments have provided us with understanding about the trends in productivity associated with different crop sequences and tillage operations. Since their inception, we now use LTAE's to help identify factors affecting sustainability and environmental quality as well as species impacts in response to change.

While we know a lot about the effect of systems on soil health ("knowns"), there are things we have not yet parameterised ("known unknowns", such as soil C). There are other things we have not even considered. Dealing with "unknown unknowns" is difficult to cost and plan for, but having well planned and suitably resourced long-term experiments can play a vital role in such studies. As Rassmussen et al. (1998) indicated, "We need continuity with the past to better predict the future."



Google Earth/DigitalGlobe view of LR1 showing the plot layout. All plots were originally one acre each. In 1986, they were split, with the southern half using the latest cultivars while the northern half retained the traditional variety Ghurkha wheat.

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The Essential Role of Soil Organic Matter in Crop Production and the Efficient use of Nitrogen and Phosphorus

By Johnny Johnston

The role of soil organic matter (SOM) in supporting the nutrient requirements of high crop yields is fundamental, especially as crop yield potential continues to improve. Lessons on N and P interactions with SOM and its support of high crop yields are well illustrated here through examples gleaned from long-term research conducted at Rothamsted.

A first example of the contribution of SOM towards enhancing crop productivity is provided here through use of data from the Hoosfeld Continuous Barley experiment at Rothamsted. Started in 1852 on a silty clay loam soil, the Hoosfeld site received annual application of NPK fertilizers, or farmyard manure (FYM) at 35 t/ha, which produced soils that now have 1.74 and 6.16% SOM, respectively. Each year since 1968, four amounts of fertilizer N (0, 48, 96, and 144 kg N/ha) are applied to these soils. Beginning in the mid 1970s, **Figure 1** plots changes in grain yield of three successive cultivars of spring barley, each with higher yield potential than its